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PULSED POWER SYSTEM INCLUDING A PLASMA OPENING SWITCH

[0001]   This application claims the benefit of U.S. Provisional Application Ser.
60/555,937 filed March 24, 2004.

Technical Field

[0002]   The invention relates generally to energy storage and compression. The
invention relates more particularly to opening switches and pulsed power generation
from stored inductive energy, and applications such as X-ray and nuclear energy
production.

Background Art

[0003]   Pulsed power has a number of military, industrial, and scientific
applications. For example, the U.S. Department of Defense has been using a variety of
pulsed power devices such as the Z accelerator at Sandia National Laboratory for
emulating nuclear weapon effects and verifying computer models. The Z machine is said
to serve as a model for a larger X-1 machine, which should provide enough X-ray energy
and power to implode fusion capsules of deuterium and tritium to achieve high-yield
fusion.

[0004]   For most applications, a high-voltage capacitor bank is discharged for
pulsed power production. Unfortunately, the energy storage density of a typical high-
voltage capacitor is relatively low, especially if the capacitor is rated for repetitive
operation. Moreover, a fast current rise is important for obtaining not only a high pulsed
power level but also a high X-ray or neutron yield. A fast current rise requires high
voltage and low inductance. (See, e.g., U.S. Patent 4,446,096 issued May 1, 1984.)

[0005]   Due to the limitations of capacitor banks, there has been considerable
effort toward developing pulsed power generators using stored inductive energy. There
are a number of relatively low cost electrical power sources that provide stored inductive
energy and have a relatively high energy density. These electrical power sources include
homopolar generators, compensated alternators, and explosively-driven magnetic flux
compressors. An opening switch, however, is needed for obtaining pulsed power having
a fast current rise from the stored inductive energy.

[0006] For example, to power a dense plasma focus with an explosive generator, a useful switch would interrupt a few megamperes in less than one microsecond and remain open for the 3 to 4 microsecond pulse delivered to the device. (Freeman et al., "Plasma Focus Experiments Powered by Explosive Generators," LA-UR-83-1083, Los Alamos National Laboratories, Los Alamos, 1983, p. 13.)

[0007] Efforts toward development of a suitable opening switch are described in G. D. Roy, "High Power, High Repetition Rate Switches: An Overview," Naval Research Review, Vol. 2, 1990, p. 17-24. Desired attributes of the switch are fast opening, fast recovery to achieve high repetition rates, controllable and long conduction time, low resistance during conduction, fast rise of impedance during opening, high impedance after opening, large currents, large stand-off voltage, and jitter-free operation. The plasma flow switch is mentioned as having conduction time up to 10^{-5} seconds and opening time in the 100 nanosecond time scale, and as of 1990, useful only in very high power (terrawatt), low impedance (10 ohm), single shot, staged pulsed power systems. (Page 19.)

Disclosure of Invention

[0008] In accordance with a basic aspect, the invention provides a pulsed power system for supplying pulsed power to a load. The pulsed power system has an inductive energy storage circuit including a current source and a plasma opening switch. The plasma opening switch has a transmission line coupling the current source to the load for supplying current to the load. The transmission line extends away from a first region toward a second region near the load. The plasma opening switch has a closed state and an open state. The plasma opening switch changes from the closed state to the open state when a plasma discharge in the plasma opening switch is driven by magnetic force from the first region toward the second region. The pulsed power system includes electrical conductors arranged for providing a stabilizing magnetic field configuration in the first region to magnetically latch the plasma discharge in the first region during charging of the inductive energy storage circuit with current from the current source, and current flowing along the transmission line from the current source to the load tends to disrupt the stabilizing magnetic field configuration and unlatch the plasma discharge from the first region and drive the plasma discharge toward the second region.

[0009] In accordance with another aspect of the invention, the plasma discharge in the first region includes at least one array of plasma discharge elements. The plasma

discharge elements in the array include a first plasma discharge element furthest from the second region and a last plasma discharge closest to the second region. The plasma discharge elements in the array are coupled to each other so that opening of the first plasma discharge element causes a sequential opening of the other plasma discharge elements in the array.

Brief Description of the Drawings

[00010]   Further objects and advantages of the invention will become apparent upon reading the following detailed description in view of the drawings, in which:

[00011]   FIG. 1 is a diagram of a coaxial conductor configuration showing that a current in an inner conductor can stabilize an outer conductor shell carrying twice the current from electromagnetic force that would otherwise tend to cause an inward radial collapse of the outer conductor shell;

[00012]   FIG. 2 shows the coaxial conductor configuration of FIG. 1 after an inward radial collapse of the outer conductor shell;

[00013]   FIG. 3 shows a schematic diagram of a pulsed power system in accordance with one aspect of the present invention, during accumulation of inductive energy when a plasma opening switch of the pulsed power system is in a closed state;

[00014]   FIG. 4 shows the pulsed power system of FIG. 3 after a trigger pulse has been applied to cause the plasma opening switch to change from the closed state to an open state;

[00015]   FIG. 5 shows the pulsed power system of FIG. 3 when the plasma opening switch has begun to open and drive plasma along a magnetically insulated transmission line toward a load;

[00016]   FIG. 6 shows the pulsed power system of FIG. 3 when the plasma has been driven along the transmission line and has reached a region near the load;

[00017]   FIG. 7 shows a more detailed schematic diagram of the pulsed power system of FIG. 3;

[00018]   FIG. 8 shows a top view of an insulator plate or ring for the pulsed power system of FIG. 3;

[00019]   FIG. 9 shows a top view of a pair of spaced electrodes in the pulsed power system of FIG. 3;

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[00020]   FIG. 10 shows a cross-section of the pair of spaced electrodes in the pulsed power system of FIG. 3 along line 10-10 in FIG. 9;

[00021]   FIG. 11 shows a cross-section of the pair of spaced electrodes in the pulsed power system of FIG. 3 along line 11-11 in FIG. 9;

[00022]   FIG. 12 shows a bottom view of the pair of spaced electrodes in the pulsed power system of FIG. 3;

[00023]   FIG. 13 shows a schematic diagram of an alternative bipolar design for a pulsed power system in accordance with the invention;

[00024]   FIG. 14 shows a cross section of the alternative bipolar design for the pulsed power system of FIG. 13 from a vantage point similar to FIG. 10;

[00025]   FIG. 15 shows graphs of current as a function of time for self-triggering of the plasma opening switch in the pulsed power system of FIG. 3;

[00026]   FIG. 16 shows a schematic diagram of a circuit for producing the current functions of FIG. 15 by inserting a resistance in one of the circuit paths;

[00027]   FIG. 17 shows a schematic diagram of a circuit for producing the current functions of FIG. 15 by different size and phase placement of stator windings on a compensated alternator;

[00028]   FIG. 18 shows an exploding wire configuration for initiating a plasma discharge;

[00029]   FIG. 19 shows a pseudo-spark generator configuration for initiating a plasma discharge;

[00030]   FIG. 20 shows a laser configuration for initiating a plasma discharge;

[00031]   FIG. 21 is a schematic diagram, in lateral cross-section, of a plasma focus or spheromac fusion-fission reactor including a circular array of pulsed power systems as shown in FIG. 3 or FIG. 13 supplying pulsed power to a common load at a central location in the reactor;

[00032]   FIG. 22 is a top view of the fusion-fission reactor of FIG. 21;

[00033]   FIG. 23 is a top view of one explosively-driven magnetic flux compressor between two excitation field coils;

[00034]   FIG. 24 is a lateral cross-section of the explosively-driven magnetic flux compressor along line 24-24 in FIG. 23;

[00035]   FIG. 25 is an oblique view of a finite element model of electrical conductors that establish the stabilizing magnetic field configuration in a respective one of the opening switches;

[00036]   FIG. 26 is a top view of the finite conductor elements of FIG. 23 and the magnetic field, at a horizontal bisecting plane, produced by current flowing in the finite conductor elements;

[00037]   FIG. 27 is an oblique view of the central finite conductor element of FIG. 25;

[00038]   FIG. 28 is a top view of the central finite conductor element and its magnetic field contribution, at the horizontal bisecting plane;

[00039]   FIG. 29 is an oblique view of the finite element model of FIG. 25 after removal of the central finite conductor element;

[00040]   FIG. 30 is a top view of the finite element model of FIG. 29 and its magnetic field contribution, at the horizontal bisecting plane;

[00041]   FIG. 31 is a top view of conductors in a finite element model of a circular array of opening switches;

[00042]   FIG. 32 is an oblique view of the conductors in the finite element model of the circular array of opening switches of FIG. 31;

[00043]   FIG. 33 is a top view of the finite element model of a single one of the opening switches in the array of FIG. 31, and the magnetic field at the horizontal bisecting plane;

[00044]   FIG. 34 is a top view similar to FIG. 33 but showing the magnetic field contribution when the central finite conductor element (representing the plasma discharge in the single one of the opening switches) is removed;

[00045]   FIG. 35 is a top view similar to FIG. 34 but for a scaling up of the magnetic field contribution by a factor of 5 to better show the confining quadrupole field configuration in the central region of the plasma discharge;

[00046]   FIG. 36 is a top view of a finite element model similar to FIG. 31 but for a state similar to FIG. 5 in which the plasma discharge in each opening switch has been displaced toward the load at a central location with respect to the circular array;

[00047]   FIG. 37 is an oblique view of the conductors in the finite element model of the circular array of opening switches of FIG. 36;

[00048]   FIG. 38 is a top view of one of the opening switches in the circular array of FIG. 36 and the magnetic field in the horizontal bisecting plane, which shows that this one of the opening switches has become magnetically insulated;

[00049]   FIG. 39 is a top view of a finite element model similar to FIG. 31 but for a hypothetical case where the single one of the opening switches fails to be triggered and is presumed (incorrectly) not to open;

[00050]   FIG. 40 is an oblique view of the finite element model of FIG. 39;

[00051]   FIG. 41 is a top view showing the magnetic field in the horizontal bisecting plane for the single one of the opening switches;

[00052]   FIG. 42 is a top view of a finite element model for a case where a single one of the opening switches in the circular array is in an open state;

[00053]   FIG. 43 is an oblique view of the finite element model of FIG. 42;

[00054]   FIG. 44 is a top view showing the magnetic field (scaled up by a factor of 5) in the horizontal bisecting plane at an opening switch neighboring the single one of the opening switches that is in the open state;

[00055]   FIGS. 45 to 47 are similar to FIGS. 42 to 44, respectively, and show the case where the plasma discharge of the single one of the opening switches has progressed further toward the load at the central location with respect to the circular array; and

[00056]   FIGS. 48 to 50 shows a case where an opening switch is in a closed state and neighboring opening switches in the circular array have been triggered into an opening state.

[00057]   FIG. 51 shows a schematic diagram of a pulsed power system in accordance with another aspect of the present invention, in which a series of opening switches are cascaded so that the opening of a first one of the switches will cause the sequential opening of the other switches in the series and the build-up of a current pulse along a transmission line shared by the opening switches in the series; and

[00058]   FIG. 52 shows a top view of an insulator plate having a series of radial channels, including a radial channel for receiving the series of opening switches shown in FIG. 51.

[00059]   While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that it is

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not intended to limit the form of the invention to the particular forms shown, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

Mode(s) for Carrying Out the Invention

5   [0001]   Pulsed-power systems often use a magnetically insulated transmission line to deliver power to a load. The load, for example, is a pinched plasma column, an imploding liner for a magnetized plasma target, a conical or hyperbolic array of fine wires for X-ray production, or a fusion fuel target or hohlraum for inertially confined fusion. When power is applied to the transmission line, any gas between the conductors

10   of the transmission line is converted to plasma by the electric field in the transmission line. The resulting plasma is driven along the transmission line toward the load by electromagnetic Lorentz force (dF = I dl x B) at the Alfvén velocity ($V_A = B/(\mu_o \rho_m)^{1/2}$). The plasma causes the transmission line to function as a plasma opening switch. In particular, there is a delay in the application of power to the load. This delay is

15   approximately the time that it takes for the plasma to be driven along the transmission line. This delay can have a beneficial effect if the delay is matched to the rise time of current from the circuitry that applies power to the transmission line.

        [0002]   Many pulsed power systems intentionally create plasma in a magnetically insulated transmission line in order to provide a plasma opening switch for

20   increasing the rate at which current is applied to the load. Such a plasma opening switch is an integral component of a dense plasma focus device, in which the load is a z-pinched plasma column formed by the radial collapse of plasma including some plasma from the transmission line. Such a plasma-opening switch is also an integral part of a plasma flow switch.

25   [0003]   The present invention is based on magnetic latching of a plasma flow switch in order to provide a stable closed state. This has the effect of increasing the delay provided by the plasma flow switch and reducing the on-resistance of the plasma flow switch during the closed state. It will be shown below that such magnetic latching is practical because only a fraction of the current applied to the transmission line is

30   needed for holding off the flow of plasma toward the load, and this can be done in such a way that the plasma flow switch switches to a magnetically insulated state once there is a flow of plasma toward the load. In other words, the flow of plasma itself can cause a switching from the stable closed state to the open state. Moreover, the plasma discharge

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in the stable closed state can be established at an array of locations, and the switching of

the plasma discharge from the closed state to the open state at one location will trigger

the switching of the plasma discharges at neighboring locations from the closed state to

the open state. Therefore, the switching process can occur very fast over a large area.

[0004]   FIG. 1 shows a coaxial conductor configuration including an outer

cylindrical conductor shell 21 and an inner cylindrical conductor shell 22. The outer

conductor shell 21 has a radius of R_2 and the inner conductor shell 22 has a radius of R_1.

The inner conductor shell 22 is shown carrying an electric current (I) in the upward

direction and the outer conductor shell 22 is shown carrying twice the current (2I) in the

opposite, downward direction. Assuming that the inner and outer conductors are co-

extensive very far in the upward and downward directions and the current density has

radial symmetry, then the magnetic field intensity (h) at a radius (r) will be a function of

the total current (i) within the radius (r) according to $h=i/2\pi r$. Therefore, in the

configuration of conductors and currents in FIG. 1, the magnetic field intensity will have

about same magnitude $H= I/2\pi R_2$ at a location just outside and inside the outer conductor

shell 21. The magnetic field will have a circumferential direction near the outer surface

of the outer conductor shell 21 tending to force the outer conductor shell inward, and the

magnetic field will have an opposite circumferential direction near the inner surface of

the outer conductor shell 21 tending to force the outer conductor shell outward.

Therefore, there will be a net electromagnetic Lorentz force ($dF = I \, dl \times B$) on the outer

conductor shell 21 of about zero.

[0005]   The configuration of conductors and electric current in FIG. 1

indicates that a central current can prevent the inward radial electromagnetic collapse of

twice that current. As described further below, this principle can be used for magnetic

latching of a plasma discharge of a plasma flow switch. The plasma discharge can be

held in a closed state corresponding to the configuration of FIG. 1, in which the plasma

discharge is analogous to the outer shell 21.

[0006]   FIG. 2 shows the coaxial conductor configuration of FIG. 1 after an

inward radial collapse of the outer conductor shell 21 to a radius of R_3. The magnetic

field for any radius greater than R_3 has the same direction. This suggests that locations at

a radius greater than R_3 can be magnetically insulated.

[0007]   FIG. 3 shows a schematic diagram of a pulsed power system for

supplying pulsed power to a load 41. The pulsed power system includes an inductive

energy storage circuit 42 including a current source 43 and a plasma opening switch 44.
The plasma opening switch 44 has a transmission line including spaced conductors 51,
52 coupling the current source 43 to the load 41 for supplying current to the load. The
transmission line extends away from a first region 45 toward a second region 46 near the
load 41. The plasma opening switch has a closed state, as shown in FIG. 3. In the closed
state, a plasma discharge 40 (represented by a pair of dashed lines) is located in the first
region 45. The plasma opening switch changes from the closed state to an open state
when the plasma discharge 40 is driven by magnetic force from the first region 45 to
toward the second region 46. The movement of the plasma discharge from the first
region 45 toward the second region 46 is show by the sequence of FIGS. 3, 4, 5, and 6.

[0008]   As further shown in FIG. 3, the pulsed power system includes
electrical conductors 47 and 48 arranged for providing a stabilizing magnetic field
configuration in the first region 45 to magnetically latch the plasma discharge in the first
region during charging of the inductive energy storage circuit 42 with current from the
current source 43. (As further described below with reference to FIG. 7, the conductors
47 and 48 are bifurcated to provide a quadrupole configuration.) However, current
flowing along the transmission line conductors 51, 52 from the current source 43 to the
load 41 tends to disrupt the stabilizing magnetic field configuration and unlatch the
plasma discharge 40 from the first region 45, as shown in FIG. 5, and drive the plasma
discharge toward the second region 46. The first region 45 becomes magnetically
insulated when the plasma opening switch is in the open state and conducting current
from the current source to the load.

[0009]   As further shown in FIG. 3, the electrical conductors 47 and 48 are in
the inductive energy storage circuit 42 and carry current from the current source 43 to the
plasma discharge 40 when the plasma discharge is in the first region 45 and the plasma
opening switch is in the closed state. The electrical conductor 48 is in a first current path
including an inductor 51 for carrying a first current component tending to magnetically
force the plasma discharge 40 toward the second region 46 when the plasma discharge is
in the first region 45. The electrical conductor 47 is in a second current path including
an inductor 52 for carrying a second current component tending to magnetically force the
plasma discharge 40 away from the second region 46 when the plasma discharge is in the
first region 45.

[00010]   As further shown in FIG. 3, the pulsed power system includes a trigger pulse generator including a capacitor 55, a conductor 56, and a closing switch 57 coupled to the first and second current paths for applying a trigger pulse to discharge the capacitor into the inductive energy circuit 42. This increases the difference between the first current component and the second current component to destabilize the stabilizing magnetic field configuration and thereby switch the plasma opening switch from the closed state to the open state. In particular, triggering of the closing switch 57 causes the closing switch 57 to close, and closing of the closing switch 57 diverts current from the inductor 52 away from the conductor 47 and into the conductor 56. This decrease in current through the conductor 47 and increase in current through the conductor 56 forces the plasma discharge 40 toward the load 41.

[00011]   As shown in FIG. 4, the closing of the closing switch 57 has caused the plasma discharge to move toward the load 41. The direct path between the electrodes 49 and 50 becomes magnetically insulated, producing a substantial voltage across the electrodes 49 and 50.

[00012]   As shown in FIG. 5, the substantial voltage across the electrodes 49 and 50 has caused isolation devices 53 and 54 to conduct current. The isolation device 53 connects the electrode 49 to the transmission line conductor 51, and the isolation device 54 connects the electrode 50 to the transmission line conductor 52. The isolation devices 49 and 50, for example, are spark gaps, metal oxide varistors, or silicon carbide varistors, which have a high incremental resistance for a low applied voltage, and a low incremental resistance for a high applied voltage. The threshold voltage for conduction of the spark gaps or varistors, for example, is slightly greater than the voltage required for sustaining the plasma discharge across the spaced electrodes 49, 50 in the first region when the plasma switch is in the closed state. The isolation devices 53 and 54 could also be semiconductor diodes, thyristors, or other kinds of switching devices. In general, the isolation devices have a relatively high resistance when the plasma discharge is in the first region 45 and the plasma opening switch 44 is in a closed state, and the isolation devices have a relatively low resistance when the plasma opening switch is in an open state.

[00013]   Once the isolation devices become conductive, the plasma discharge 40 conducts current between the transmission line conductors 51 and 52, and magnetic force drives the plasma discharge 40 toward the load 41. As shown in FIG. 6, the plasma

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discharge 40 eventually reaches the region 46 near the load, and further displacement of the plasma discharge causes the current flowing through the transmission line 44 to be applied to the load 41.

[00014]   FIG. 7 further shows three-dimensional aspects of the pulsed power system introduced in the two-dimensional schematic diagram of FIG. 2. FIG. 7 shows that the conductors 47, 48, and inductors 51 and 52 and capacitor 55 are bifurcated (into components designated with similar reference numerals having a suffix "a" or "b") to provide a quadrupole magnetic field configuration for gross MHD stabilization of the plasma discharge 40 when the plasma opening switch is in its closed state. The conductors 47a and 47b are parallel-spaced and disposed between the second region (46 in FIG. 6) and the first region (45 in FIG. 6, between the electrodes 49 and 50 in FIG. 7) so that the plasma discharge passes between the conductors 47a and 47b when the plasma opening switch changes from the closed state to the open state.

[00015]   Omitted from FIG. 7 is a dielectric structure that electrically insulates the conductors 56, 47a, 47b, 48a, and 48b from the plasma discharge and provides physical support for these conductors and the electrodes 49, 50 and the transmission line conductors 51 and 52. Such a dielectric structure is shown in FIGS. 8 to 12. This dielectric structure is a sandwich of three glass or ceramic dielectric layers that are fused together. Moreover, as will be further described below, a large-scale pulsed power system may include a circular array of circuits each as shown in FIG. 3, disposed around a common load. In this case, each of the three glass or ceramic dielectric layers is annular shaped.

[00016]   FIG. 8 shows a top view of the middle dielectric layer 61. The middle dielectric layer has a series of holes 62, 63, 64, 65, and 66 arranged in a circular pattern around a center 68 which is the central axis of a plasma discharge when the plasma flow switch is in is stable closed state. The hole 62 and 63 permit the conductors 47a and 47b of FIG. 7 to pass through the middle dielectric layer 61. The holes 64 and 65 permit the conductors 48a and 48b to pass through the middle dielectric layer 61. The hole 66 permits the conductor 56 to pass through the middle dielectric layer 61. The middle dielectric layer 61 defines a channel 67 through which the plasma discharge moves from the center 68 toward the load.

[00017]   FIG. 9 shows a top view of the plasma opening switch once components have been assembled onto the middle dielectric layer. These components

include an upper dielectric layer 70, a metal plate 71 interconnecting the conductors 47a, 47b, 48a, 48b, and 56 to the upper electrode 49, and the upper transmission line conductor 51. Also seen in FIG. 9 are a number of bus bars for connections underneath the dielectric layers. These bus bars include a bus bar 72 connected to the conductor 48a, a bus bar 73 connected to the lower electrode (50 in FIG. 7), a bus bar 74 connected to the conductor 56, a bus bar 75 connected to the capacitors (55a and 55b in FIG .7), and a bus bar 76 connected to the conductor 48b.

[00018] FIG. 10 shows a cross-section of the plasma opening switch in the vicinity of the electrodes 49 and 50. The three dielectric layers 70, 61, and 77 are shown sandwiched together. Also seen in FIG. 10 are lower bus bars 78 and 79, which are connected to the conductors 47a and 47b.

[00019] FIG. 11 shows another cross-section of the plasma opening switch in the vicinity of the electrodes 49 and 50. FIG. 11 shows the connection of the bus bar 74 to the conductor 56 and the connection of the bus bar 73 to the lower electrode 50. It is also seen that the dielectric layers 70, 61 and 77 are sandwiched between the transmission line conductors 51 and 52.

[00020] FIG. 12 shows a bottom view of the plasma opening switch in the vicinity of the lower electrode 50. This shows the connections of the bus bars 72, 73, 76, 78, and 79 to the conductor 48a, electrode 50, conductor 48b, conductor 47a, and conductor 47b, respectively.

[00021] The maximum voltage that can be tolerated across the electrodes in the pulsed power system 44 of FIG. 3 is limited by dielectric breakdown between the lower electrode 50 and the conductors 47 and 48. The pulsed power system 44 is essentially a "single ended" design in which the lower electrode 50 can be grounded. This has the advantage of simplicity in construction and ease of insulating the bus bars 72, 73, 86, 78, and 79 of FIG. 12 in a pool of dielectric liquid such as mineral oil.

[00022] FIG. 13 shows a pulsed power system 80 having a bipolar design permitting the maximum voltage across the electrodes 84 and 85 to be doubled in comparison to the single ended design of FIG. 3. The pulsed power system 80 in FIG. 13 has a load 81 connected to transmission line conductors 82 and 83. The electrodes 84 and 85 provide an initial plasma discharge 86 and are coupled to the transmission line conductors 82 and 83, respectively, via isolation devices 87 and 87, respectively.

[00023]   A compensated alternator 91 functions as a bipolar current source to provide current to the electrodes 84 and 85, and the current path includes conductors 110 and 96 providing a stabilizing quadrupole magnetic field configuration for the initial plasma discharge 86. The compensated alternator 90 includes a rotor 91 and stator coils

5   92, 93, 94 and 95, and a switch 100 is closed so that a current pulse is generated in the stator coils. Further details regarding the construction of a suitable compensated alternator are found in Weldon et al. U.S. Patent 4,841,217 issued June 20, 1989, incorporated herein by reference, and Pratap et al. U.S. Patent 5,210,452, issued May 11, 1993, incorporated herein by reference.

10   [00024]   For switching the plasma opening switch of the electrodes 84 and 85 from a closed to an open state, a closing switch 99 discharges a capacitor 98 so as to divert current from the conductor 110 to a conductor 97.

[00025]   FIG. 14 shows a cross-section of the pulsed power system of FIG. 13 in the vicinity of the electrodes 84 and 85. In comparison to the cross-section of FIG. 10

15   for the single-ended design of FIG. 3, the cross-section in FIG. 14 for the bipolar design of FIG. 13 has a set of upper bus bars 104, 105 that are similar to a set of lower bus bars 106, 107.

[00026]   For some applications, it is desirable to configure the inductive storage circuit (42 of FIG. 3) to promote self-triggering of the opening switch of the

20   pulsed power system. This can be done by configuring the inductive storage circuit so that that when the plasma opening switch is in the closed state and the inductive energy storage circuit becomes charged by the current source, the difference between the first current component (I_1) to the conductor 48 and the second current component (I_2) to the conductor 47 is an increasing function of time so that the stabilizing magnetic field

25   configuration becomes destabilized for switching of the plasma opening switch from the closed state to the open state. For example, as shown in FIG. 15, the first current component (I_1) can be an increasing function of time 111 when the second current component (I_2) is an increasing and then a decreasing function of time.

[00027]   FIG. 16 shows one way of configuring the inductive storage circuit to

30   obtain the current functions of FIG. 15. In FIG. 16, a resistance 113 is inserted in the second circuit path providing the second current component (I_2), so that the second circuit path has a hither resistance than the first circuit path providing the first current

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component (I_1). Therefore, the magnitude of the second current component (I_2) will reach a peak and fall off before the first component (I_1) reaches a peak.

[00028]   FIG. 17 shows another way of configuring the inductive storage circuit to obtain the current functions of FIG. 15. In FIG. 16, the inductances 51 and 52 in the respective circuit paths providing the first and second current components (I_1 and I_2) are provided by respective stator windings of a compensated alternator 114, and these stator windings have a spatial extent and relative phase placement to provide the desired current functions of FIG. 15.

[00029]   FIGS. 18 to 20 show various means for initiating a plasma discharge between a pair of electrodes, such as the electrodes 49 and 50 in FIG. 3 or 84 and 85 in FIG. 13. In some cases, dielectric breakdown voltage across the electrodes will be relatively low in comparison to the voltage produced by the current source 43 in FIG. 3 so that no additional means will be needed for initiating the plasma discharge. In such cases, the discharge will occur shortly after the current source 43 is activated, for example when a compensated alternator is switched on, or an explosive magnetic flux compression generator or is detonated.

[00030]   As shown in FIG. 18, for single-shot applications, a thin metal wire 123 can be strung from a plug 124 in the upper electrode 121 to an insert 125 in the lower electrode 122 to initiate a plasma discharge between the electrodes when the current source is activated. In this case, the wire 123 will explode and provide a metal vapor arc between the electrodes 121, 122.

[00031]   As shown in FIG. 19, for multi-shot applications, a pseudo-spark generator 133 can provide a beam 134 of photons, ions, or electrons having sufficient energy to initiate a plasma discharge between the electrodes 131 and 132.

[00032]   As shown in FIG. 20, for repetitive operation, a laser 143 can provide a beam of photons 144 for initiating a plasma discharge between the electrodes 141. For example, the electrode 141 is an anode and the electrode 142 is a cathode. For operation when there is a very low pressure of gas between the electrodes 141 and 142, the laser 143 is a carbon dioxide laser that heats the cathode to initiate thermionic emission. For operation when there is a relatively high pressure of gas between the electrodes 141 and 142, the laser is an excimer laser providing a beam of ultraviolet radiation that ionizes the gas between the electrodes 142 and 143. To reduce undesirable effects of electro-

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erosion, the cathode 142 can have a pool of liquid metal 145 such as lithium for supporting a plasma arc discharge.

[00033]   The pulsed power system 44 of FIG. 3 can be used in a nuclear fusion reactor such as the fusion-fission reactor shown in FIG. 21. In this case, the transmission line conductors of the opening switch include electrodes of a plasma flow switch, namely, a dense plasma focus device. The reactor produces a dense plasma focus 150 at a central location between a central anode 151 and a cathode including a pool of molten lithium 152. Respective transmission line plates 153, 154 couple opening switches 155, 156 to the central anode 151 and cathode 152. The opening switches 155, 156 are triggered in synchronism by discharging respective capacitors 157, 158. Compensated alternators 159, 160 provide current to the opening switches. An inner blanket of actinide waste 161 (such as depleted uranium) and an outer blanket of lithium 162 provide radiation shielding and breed tritium for fueling of the plasma focus with a mixture of deuterium and tritium gas.

[00034]   By magnetizing the transmission line plates 153, 154, the fusion-fission reactor operates as a spheromac device instead of a dense plasma focus device. The transmission line plates are magnetized by energizing electromagnet coils 163 and 164, so that helicity is injected into the plasma discharge driven from the opening switches 155, 156 inward toward the central region of the reactor. A pair of Helmholtz coils 165, 166 above and below the central region of the reactor can null out the magnetic field at the central region of the reactor by opposing the magnetic field from the electromagnet coils 163 and 164.

[00035]   As shown in FIG. 22, the opening switches 155, 156 are just two switches in a circular array of opening switches, and the compensated alternators 159, 160 are just two compensated alternators in a circular array of compensated alternators. Respective excitation field coils 171, 172 and 173, 174 for the compensated alternators 159, 160 are shared with neighboring compensated alternators in the array, so that the excitation field for the compensated alternators is confined to a toroidal region of the compensated alternators.

[00036]   For single-shot applications, explosive magnetic flux compression generators can be used in lieu of the compensated alternators of FIG. 22. The excitation field coils can be kept in place for exciting the magnetic flux compression generators.

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FIG. 23, for example, shows an explosive magnetic flux compression generator 183 between two field coils 181 and 182.

[00037]   FIG. 24 shows a cross-section of the explosive magnetic flux compression generator 183. The explosive magnetic flux compression generator 183 includes alternate layer sheets of explosive 185, metal conductor 186, and insulator 187 such as polyethylene or polyvinyl chloride. Detonation of the explosive layers causes loops of the metal conductor layers to implode upon the insulator layers and compress the magnetic flux from the field coils trapped within the metal conductor loops. The loops of metal conductor are connected in parallel for increased current, and in series if needed to provide sufficient voltage for overcoming the voltage drop of the plasma discharge across the opening switch.

[00038]   As described above, the opening switch 44 in FIG. 3 is capable of switching from a closed state in which the plasma discharge 40 is held within a stabilizing magnetic field configuration to an open state in which the region 45 between the electrodes 49 and 50 becomes magnetically insulated. Such operation of the opening switch 40 is demonstrated by computer simulation using a finite element analysis program as listed below.

[00039]   FIG. 25 is an oblique view of a finite element model of the electrical conductors 47a, 47b, 48a, 48b that establish the stabilizing magnetic field configuration in the opening switch as was shown and described in FIGS. 7 to 12. It is assumed that the current flowing downward through the plasma discharge 40 is supplied by an upward one-quarter of the current through each of the conductors 47a, 47b, 48a, 48b. FIG. 26 shows the resulting magnetic field, at a horizontal bisecting plane, produced by this current distribution through the finite element model of FIG. 25.

[00040]   As introduced in FIGS. 3 to 6, the magnetic force upon the plasma discharge determines a sequence of operation of the plasma opening switch. To better show the spatial distribution of this force upon current flowing in the plasma discharge, the magnetic field of FIG. 26 can be split into a contribution to the magnetic field due to the solid conductors (such as the current elements 47a, 47b, 48a, 48b) and a contribution to the magnetic field due to the current flowing through the plasma discharge itself. For example, the current flowing through the plasma discharge 40, as shown in FIG. 27, produces the magnetic field contribution shown in FIG. 28, in accordance with the Biot-Savart law. However, this magnetic field contribution caused by the current flowing

through the plasma discharge 40 does not result in any net force upon the plasma discharge as a whole.

[00041]   FIG. 29 shows the finite element model of the solid conductors in the opening switch. The current through these solid conductors produces the magnetic field contribution shown in FIG. 30. This is a magnetic quadrupole field configuration providing a local minimum of magnetic force upon the plasma discharge at a central location between the conductors 47a, 47b, 48a, and 48b. This magnetic field configuration tends to produce a net force upon the plasma discharge 40 tending to confine the plasma discharge to the central location between the conductors 47a, 47b, 48a, and 48b.

[00042]   As described above with respect to FIG. 8 and FIGS. 21 and 22, it is desired to use a circular array of the opening switches in order to supply pulsed power to a common load at a central location with respect to the circular array. In this case, the magnetic field in the neighborhood of each switch is affected by the current flowing through all of the current elements in all of the switches of the array. For example, FIG. 31 is a top view of conductors in a finite element model of a circular array of opening switches; FIG. 32 is an oblique view of the conductors in the finite element model of the circular array of opening switches of FIG. 31; and FIG. 33 shows the magnetic field in the neighborhood of a single opening switch 190 in the circular array.

[00043]   FIG. 34 is a top view similar to FIG. 33 but showing the magnetic field contribution when the central finite conductor element (representing the plasma discharge in the single one of the opening switches) is removed. This magnetic field configuration in FIG. 34 is a quadrupole configuration similar to FIG. 30. The field configuration of FIG. 34 is shown in FIG. 35 after scaling up by a factor of five. It should be apparent from FIG. 35 that the plasma discharge in the switch 190 will be confined to the central location with respect to the conductors 47a, 47b, 48a, 48b.

[00044]   FIG. 36 is a top view of a finite element model similar to FIG. 31 but for a state similar to FIG. 5 in which the plasma discharge in each opening switch has been displaced toward the load at a central location with respect to the circular array. FIG. 37 shows an oblique view of the finite element model of FIG. 36. FIG. 38 shows the magnetic field configuration in the neighborhood of one switch 200. This magnetic field configuration in FIG. 38 shows that the opening switch 200 has become magnetically insulated.

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[00045]   FIG. 39 is a top view of a finite element model similar to FIG. 31 but
for a hypothetical case where a single opening switch 210 fails to be triggered and is
presumed (incorrectly) not to open. FIG. 40 shows an oblique view of the finite element
model of FIG. 39. FIG. 41 shows the magnetic field in the neighborhood of the single
opening switch 210. The magnetic field configuration in FIG. 41 demonstrates that the
opening of the other switches in the array will cause the opening switch 210 to become
magnetically insulated and cause the plasma discharge of the opening switch 210 to be
driven toward the load at the central location with respect to the array.

[00046]   Further computer simulations show that the opening of one switch in
the array may cause neighboring switches to open, so that the triggering of a single
switch may cause the entire array to open. The array of opening switches will function
as the dual of a Marx bank of closing switches. For example, FIG. 42 is a top view of a
finite element model for a case where a single opening switch 215 in the circular array is
in an open state. FIG. 43 is an oblique view of the finite element model of FIG. 42. FIG.
44 shows the magnetic field (scaled up by a factor of five) in the neighboring switch 216.
The opening of the switch 215 has disrupted the magnetic field configuration for the
neighboring switch 216. FIGS. 45 to 47 show that further opening of the switch 215
further disrupts the magnetic field configuration for the neighboring switch 216.

[00047]   FIGS. 48 to 50 are similar to FIGS. 42 to 44, respectively, so that FIG.
50 shows the magnetic field for one of the opening switches when each of its two
neighboring opening switches has been triggered into an opening state. From FIGS. 48
to 50 it appears that there is no need to trigger all of the switches in the array for fast
opening of the entire array. Instead, including an even number of switches in the array
and simultaneously triggering every other switch in the array can achieve fast opening of
the entire array. At some expense of asymmetrical implosion, a fewer number of the
switches could be triggered simultaneously. For example, in an array having thirty-six
switches, every sixth switch in the array could be triggered simultaneously.

[00048]   FIG. 51 shows a schematic diagram of a pulsed power system in
accordance with another aspect of the present invention, in which a series of plasma
discharge elements are cascaded so that the opening of a first one of the switches will
cause the sequential opening of the other switches in the series and a build-up of a
current pulse along a transmission line shared by the plasma discharge elements in the
series. For example, the pulsed power system in FIG. 51 includes a load 241, a current

source 243, electrodes 249, 250 for producing a first discharge element, transmission line conductors 251, 252, isolation devices 253, 254, a capacitor 255, and a closing switch 257, which are similar to the respective elements 43, 49, 50, 51, 52, 53, 54, 55, and 57 in FIG. 3. The pulsed power system of FIG. 51 in addition includes a series of electrodes, conductors, and isolation devices (261, 262, 263, 264, 265) for supporting respective plasma discharge elements (shown in dashed lines) aligned along a direction from the first pair of electrodes 249, 250 towards the load 241. Due to the coupling by the isolation devices between the respective pairs of electrodes supporting the respective plasma discharge elements, opening of the first plasma discharge element (triggered by the closing of the switch 257) causes a sequential opening of the other plasma discharge elements in the array.

[00049]   The plasma discharge elements can be cascaded in the fashion shown in FIG. 51 in order to reduce the size of the high-voltage capacitor 255 needed for triggering the series of the plasma discharge elements. The plasma discharge elements can also be cascaded in this fashion in order to reduce the amount of current that need be conducted by each plasma discharge element until the series of plasma discharge elements is triggered. The amount of current that need be conducted by plasma discharge element can be reduced in order to reduce the power loss and heat dissipation for each plasma discharge element. For example, the current conducted by each closed switch could be limited to no more than about 1 mega-ampere to promote discharge stability. The current density could be limited to permit the use of thermionic or field emitters for initiating and sustaining each plasma discharge element. This could permit the use of relatively low voltage current sources such as electrolytic capacitors and ultra-capacitors. For example, table-top pulsed power generators could use a number of capacitor modules, each including one or more electrolytic capacitors or a multiplicity of ultra-capacitors, a crowbar diode, and a silicon controlled rectifier for discharging current from the capacitors to one or more of the plasma discharge elements.

[00050]   In practice, each plasma opening switch (e.g., 155, 156) shown in FIG. 22 could be replaced with an array of plasma discharge elements as shown in FIG. 51 in order to reduce the size of the high-voltage capacitors for triggering the opening switch array. For example, FIG. 52 shows a top view of an insulator plate 270 that could be used in such a pulsed power generator. The insulator plate 270 has a series of radial channels such as radial channel 271 for receiving the series of plasma discharges shown

in FIG. 51. The insulator plate 270 could be cast from a ceramic cement composition, such as the CeraLith (Trademark) brand of inorganic polymer ceramic cement described in U.S. Patent 5,766,337.

[00051]   Following is a listing of the finite element analysis program, in the C programming language, and in particular the version of the program that generated FIGS. 36 to 38:

```
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <sys/stat.h> /* for mode definitions */
#include <math.h>


#define NSIZE   1053724  /* graphics file buffer size in bytes */
#define BITMAP  0X2F0  /* graphics file bitmap offset in bytes */
#define LINBYT  319     /* bitmap bytes per row of pixels */
#define ORIGY   1650    /* y pixel coordinate of center of picture */
#define ORIGX   1276    /* x pixel coordinate of center of picture */
#define MAXPX   2550    /* maximum pixel per horizontal line */
#define MAXPY   3300    /* maximum pixel per vertical line */


#define NGDX    5          /* Range of X coord. index in field position, -NGDX to
+NGDX */
#define NGDY    4          /* Range of Y coord. index in field position, -NGDY to -
NGDY */
#define NPTS    (2*NGDX+1)*(2*NGDY+1)  /* No. of points at which H field is
calculated */


#define NCPERS  13        /* No. of current elements in single switch */
            /* Current elements in the discharge are at 0, NCPERS, 2*NCPERS, ... */
#define NSWITCH 24        /* No. of switches per 2*pie radians */
#define NCUR    NCPERS*NSWITCH  /* No. of current elements in the entire array */
```

```c
char buf[NSIZE];        /* graphics buffer */
long nbytes;            /* no. of bytes used in graphics file */


void input_graph();     /* function to input graphics file to buffer */
void output_graph();    /* function to output buffer to graphics file */
void plot_point();      /* function to plot a point */
void plot_line();       /* function to plot a line */
void plot_circle();     /* function to plot a circle */
void plot_dline();      /* function to plot 2-pix wide line */
void plot_tline();      /* function to plot 3-pix wide line */
void plot_qline();      /* function to plot 4-pix wide line */
void plot_current();    /* function to plot current of xi, yi, xf, yf */
void plot_field();      /* function to plot field of x, y, Hx, Hy */
void plot_oblique();    /* function to plot oblique view */


void input_graph()
{
                /*      Input graphics file header and bitmap into graphics buffer */
FILE *fopen(), *fp1;
int val;
fp1 = fopen("C:/G300IN.TIF", "rb");
if (fp1 == NULL) {
printf("add: Error -- C:/G300IN.TIF does not exist\n");
exit(1);
}
for (nbytes = 0; nbytes< NSIZE; nbytes++){
    if((val = getc(fp1))!=EOF){
    buf[nbytes] = val;
    }
    else{
    buf[nbytes] = val;
    break;
    }
```

```
    }
    }
    void output_graph()

    {
5   FILE *fopen(), *fp2;
    long m;
                      /*  Output graphics buffer to graphics output file  */
    fp2 = fopen("C:/Graphot.tif", "wb+");
    if (fp2 == NULL) {
10  printf("add: Error -- C:/GRAPHOT.TIF not created\n");
    exit(1);
    }
     for (m = 0; m<nbytes; m++){
     putc(buf[m], fp2);
15   }
    }
              /*     Plot Point (vx, vy) with respect to origin (ORIGX, ORIGY) */
    void plot_point(vx, vy)
    long vx, vy;
20  {
    long px, py, bufadr, bytx, bit;
    unsigned mask;
    px = ORIGX + vx;
    if (px < 50) px = 50;
25  if (px > MAXPX-50) px = MAXPX-50;
    py = ORIGY - vy;
    if (py < 50) py = 50;
    if (py > MAXPY-50) py = MAXPY-50;
    bytx = px/8;
30  bit = px - bytx*8;
    bufadr = BITMAP + py*LINBYT+bytx;
    if (bufadr > NSIZE - 1) bufadr = NSIZE -1;
                      /* set indicated bit of buf[bufadr] */
```

```
    mask = 128;

    mask = mask >> bit;

    buf[bufadr] = buf[bufadr] | mask;

    }

    void plot_line (vxi, vyi, vxf, vyf)

    long vxi, vyi, vxf, vyf;

    {

    long dvx, dvy, absdvx, absdvy, nx, ny, sum;

                    dvx = vxf-vxi;

                    dvy = vyf-vyi;

                    absdvx = dvx;

                    if (absdvx < 0) absdvx = -absdvx;

                    absdvy = dvy;

                    if (absdvy < 0) absdvy = -absdvy;

                    if (absdvx > absdvy){

                        if (vxf > vxi){

                            plot_point(vxi,vyi);

                            if (vxf!=vxi){

                                sum = absdvx/2;

                                ny = vyi;

                                for (nx = vxi +1; nx<=vxf; nx++){

                                    sum = sum + absdvy;

                                    if(sum>=absdvx){

                                        if (dvy>0){

                                            ny++;

                                        }

                                        else ny--;

                                        sum=sum-absdvx;

                                    }

                                    plot_point(nx,ny);

                                }

                            }

                        }
```

```
            else{
                    plot_point(vxf,vyf);
                    if (vxf!=vxi){
                            sum = absdvx/2;
                            ny = vyf;
                            for (nx = vxf +1; nx<=vxi; nx++){
                                    sum = sum + absdvy;
                                    if(sum>=absdvx){
                                            if (dvy>0){
                                                    ny--;
                                            }
                                            else ny++;
                                            sum=sum-absdvx;
                                    }
                                    plot_point(nx,ny);
                            }
                    }
            }
    }
    else {
            if (vyf > vyi){
                    plot_point(vxi,vyi);
                    if (vyi!=vyf){
                            sum = absdvy/2;
                            nx = vxi;
                            for (ny = vyi +1; ny<=vyf; ny++){
                                    sum = sum + absdvx;
                                    if(sum>=absdvy){
                                            if (dvx>0){
                                                    nx++;
                                            }
                                            else nx--;
                                            sum=sum-absdvy;
```

```
                    }
                    plot_point(nx,ny);
                }
            }
        }
        else{
            plot_point(vxf,vyf);
            if (vyf!=vyi){
                sum = absdvy/2;
                nx = vxf;
                for (ny = vyf +1; ny<=vyi; ny++){
                    sum = sum + absdvx;
                    if(sum>=absdvy){
                        if (dvx>0){
                            nx--;
                        }
                        else nx++;
                        sum=sum-absdvy;
                    }
                    plot_point(nx,ny);
                }
            }
        }
    }
}
void plot_circle(x,y,radius)
long x, y, radius;
{
    long np, fp;
    if(radius<0) radius = -radius;
    if(radius==0){
        plot_point(x,y);
    }
```

```
else{
    plot_point(x-radius,y);
    plot_point(x+radius,y);
    plot_point(x, y+radius);
    plot_point(x, y-radius);
    if(radius >1){
        fp = radius;
        for(np=1; np<=fp; np++){
            fp = 0.49 + sqrt(radius*radius-np*np);
            plot_point(x-np,y+fp);
            plot_point(x+np,y+fp);
            plot_point(x-np,y-fp);
            plot_point(x+np,y-fp);
            plot_point(x+fp,y-np);
            plot_point(x+fp,y+np);
            plot_point(x-fp,y-np);
            plot_point(x-fp,y+np);

        }
    }
}
}
void plot_dline(vxi, vyi, vxf, vyf)
long vxi, vyi, vxf, vyf;
{
    plot_line(vxi, vyi, vxf, vyf);
    plot_line(vxi+1, vyi, vxf+1, vyf);
    plot_line(vxi, vyi+1, vxf, vyf+1);
    plot_line(vxi+1, vyi+1, vxf+1, vyf+1);
}
void plot_tline(vxi, vyi, vxf, vyf)
long vxi, vyi, vxf, vyf;
{
    plot_line(vxi+1, vyi,  vxf+1, vyf);
```

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```
                          plot_line(vxi+1, vyi+1, vxf+1, vyf+1);
                          plot_line(vxi,   vyi+1, vxf,   vyf+1);
                          plot_line(vxi-1, vyi+1, vxf-1, vyf+1);
                          plot_line(vxi-1, vyi,   vxf-1, vyf);
                          plot_line(vxi-1, vyi-1, vxf-1, vyf-1);
                          plot_line(vxi,   vyi-1, vxf,   vyf-1);
                          plot_line(vxi+1, vyi-1, vxf+1, vyf-1);

    }
    void plot_qline(vxi, vyi, vxf, vyf)
    long vxi, vyi, vxf, vyf;
    {
                          plot_line(vxi+2, vyi+2, vxf+2, vyf+2);
                          plot_line(vxi+2, vyi+1, vxf+2, vyf+1);
                          plot_line(vxi+2, vyi,   vxf+2, vyf );
                          plot_line(vxi+2, vyi-1, vxf+2, vyf-1);
                          plot_line(vxi+1, vyi-1, vxf+1, vyf-1);
                          plot_line(vxi,   vyi-1, vxf,   vyf-1);
                          plot_line(vxi-1, vyi-1, vxf-1, vyf-1);
                          plot_line(vxi-1, vyi,   vxf-1, vyf );
                          plot_line(vxi-1, vyi+1, vxf-1, vyf+1);
                          plot_line(vxi-1, vyi+2, vxf-1, vyf+2);
                          plot_line(vxi,   vyi+2, vxf,   vyf+2);
                          plot_line(vxi+1, vyi+2, vxf+1, vyf+2);

    }
    void plot_current(fxi, fyi, fxf, fyf, PIXPERX)
    double fxi, fyi, fxf, fyf;
    long PIXPERX;
    {
                          long xi, yi, xf, yf;
                          xi=fxi*PIXPERX + 0.49;
                          yi=fyi*PIXPERX + 0.49;
                          xf=fxf*PIXPERX + 0.49;
                          yf=fyf*PIXPERX + 0.49;
```

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```
                        plot_qline(xi, yi, xf, yf);
        }
        void plot_field(fx, fy, fhx, fhy, PIXPERX, PIXPERH)
        double fx, fy, fhx, fhy;
5       long PIXPERX, PIXPERH;
        {
                        long x, y, hx, hy;
                        x=fx*PIXPERX + 0.49;
                        y=fy*PIXPERX + 0.49;
10                      hx=fhx*PIXPERH + 0.49;
                        hy=fhy*PIXPERH + 0.49;
                        plot_tline(x, y, x+hx, y+hy);
                        plot_line(x-2, y-2, x-2, y+2);
                        plot_line(x-2, y+2, x+2, y+2);
15                      plot_line(x+2, y+2, x+2, y-2);
                        plot_line(x+2, y-2, x-2, y-2);
        }
        void plot_oblique(fxi, fyi, fzi, fxf, fyf, fzf, PIXPERX)
        double fxi, fyi, fzi, fxf, fyf, fzf;
20      long PIXPERX;
        {
                        long xi, yi, xf, yf;
                        fzi = (fzi + 0.43301 * fyi);
                        fzf = (fzf + 0.43301 * fyf);
25                      fxi = (fxi + 0.125 * fyi);
                        fxf = (fxf + 0.125 * fyf);
                        xi=fxi*PIXPERX;
                        yi=fzi*PIXPERX;
                        xf=fxf*PIXPERX;
30                      yf=fzf*PIXPERX;
                        plot_qline(xi, yi, xf, yf);
        }
        main()
```

```
{

    double pie, a, b, c, d, delta;
    double bdx, bdy, bdz, blength, dx, dy, dz;
5   double xi, yi, zi, hx, hy, hz, xm, ym, zm;
    double x, y, z, bmx, bmy, bmz;
    double rsqd, rsqdp;
    double fax, fay;
    double phi, theta, sinth, costh;
10  double deltr;

    struct {
        double hx[NPTS];
        double hy[NPTS];
15      double hz[NPTS];
        double x[NPTS];
        double y[NPTS];
        double z[NPTS];
    }   field;
20  struct {
        double i[NCUR];
        double xi[NCUR];
        double yi[NCUR];
        double zi[NCUR];
25      double xf[NCUR];
        double yf[NCUR];
        double zf[NCUR];
    }   current;
    int PTS, CUR, I, J, N;
30
    FILE *fopen(), *fp;
    fp=fopen("C:/MFOUT","w");
```

```
input_graph();

/*  Set internal parameters */
pie = 3.1415926;

/*  Set input parameters */
a=0.1;
b=0.1;
c=0.1;                  /*      conductors range +c to -c           */
d=0.025;                /*      resolution of field position array    */
delta=0.001;            /*      resolution of finite current elements  */
fax = 1.0;              /* x coordinate of center of field poistion array */
fay = 0.;               /* y coordinate of center of field postion array   */
deltr = 2*a;            /*      offset of discharge in radial direction  */

/* current 0 is plasma discharge */
current.i[0]=1.0;
current.xi[0]=1-deltr;
current.yi[0]=0;
current.zi[0]=c;
current.xf[0]=1-deltr;
current.yf[0]=0;
current.zf[0]=-c;


current.i[1]=0.25;
current.xi[1]=1-deltr;
current.yi[1]=0;
current.zi[1]=-c;
current.xf[1]=1-a;
current.yf[1]=b;
current.zf[1]=-c;


current.i[2]=0.25;
```

```
        current.xi[2]=1-a;
        current.yi[2]=b;
        current.zi[2]=-c;
        current.xf[2]=1-a;
5       current.yf[2]=b;
        current.zf[2]=c;


        current.i[3]=0.25;
        current.xi[3]=1-a;
10      current.yi[3]=b;
        current.zi[3]=c;
        current.xf[3]=1-deltr;
        current.yf[3]=0;
        current.zf[3]=c;

15

        current.i[4]=0.25;
        current.xi[4]=1-deltr;
        current.yi[4]=0;
        current.zi[4]=-c;
20      current.xf[4]=1+a;
        current.yf[4]=b;
        current.zf[4]=-c;


        current.i[5]=0.25;
25      current.xi[5]=1+a;
        current.yi[5]=b;
        current.zi[5]=-c;
        current.xf[5]=1+a;
        current.yf[5]=b;
30      current.zf[5]=c;


        current.i[6]=0.25;
        current.xi[6]=1+a;
```

```
        current.yi[6]=b;
        current.zi[6]=c;
        current.xf[6]=1-deltr;
        current.yf[6]=0;
5       current.zf[6]=c;


        current.i[7]=0.25;
        current.xi[7]=1-deltr;
        current.yi[7]=0;
10      current.zi[7]=-c;
        current.xf[7]=1+a;
        current.yf[7]=-b;
        current.zf[7]=-c;


15      current.i[8]=0.25;
        current.xi[8]=1+a;
        current.yi[8]=-b;
        current.zi[8]=-c;
        current.xf[8]=1+a;
20      current.yf[8]=-b;
        current.zf[8]=c;


        current.i[9]=0.25;
        current.xi[9]=1+a;
25      current.yi[9]=-b;
        current.zi[9]=c;
        current.xf[9]=1-deltr;
        current.yf[9]=0;
        current.zf[9]=c;
30

        current.i[10]=0.25;
        current.xi[10]=1-deltr;
        current.yi[10]=0;
```

```
        current.zi[10]=-c;
        current.xf[10]=1-a;
        current.yf[10]=-b;
        current.zf[10]=-c;
5
        current.i[11]=0.25;
        current.xi[11]=1-a;
        current.yi[11]=-b;
        current.zi[11]=-c;
10      current.xf[11]=1-a;
        current.yf[11]=-b;
        current.zf[11]=c;

        current.i[12]=0.25;
15      current.xi[12]=1-a;
        current.yi[12]=-b;
        current.zi[12]=c;
        current.xf[12]=1-deltr;
        current.yf[12]=0;
20      current.zf[12]=c;

     CUR = NCPERS;
     phi = 2*pie/NSWITCH;
     theta = 0.;
25   if (NSWITCH>1)
     {
     for (I=1; I<NSWITCH; I++)
     {
     theta = theta + phi;
30   sinth = sin(theta);
     costh = cos(theta);
                for (J=0; J<NCPERS; J++)
                    {
```

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```
                     current.i[CUR] = current.i[J];
                     current.xi[CUR]=current.xi[J]*costh - current.yi[J]*sinth;
                     current.yi[CUR]=current.xi[J]*sinth + current.yi[J]*costh;
                     current.zi[CUR]=current.zi[J];
5                    current.xf[CUR]=current.xf[J]*costh - current.yf[J]*sinth;
                     current.yf[CUR]=current.xf[J]*sinth + current.yf[J]*costh;
                     current.zf[CUR]=current.zf[J];
                     CUR=CUR+1;
                     }
10      }
        }
                                /* Calculate position coordinates of field array */
        PTS = 0;
        for (I=-NGDX; I<NGDX+1; I++)
15      {
        for (J=-NGDY; J<NGDY+1; J++)
        {
        field.x[PTS] = fax + d*I;
        field.y[PTS] = fay + d*J;
20      field.z[PTS] = 0;
        PTS=PTS +1;
        }
        }
        /* clear field components for accumulation */
25      for (PTS=0; PTS<NPTS; PTS++)
        {
        field.hx[PTS]=0;
        field.hy[PTS]=0;
        field.hz[PTS]=0;
30           /* begin summation of field from all current elements in current array */
        for (CUR=0; CUR<NCUR; CUR++)
        {
        x = field.x[PTS];
```

```
y = field.y[PTS];
z = field.z[PTS];
        /*divide current structure element into N finite elements of about delta */
bdx = current.xf[CUR] - current.xi[CUR];
bdy = current.yf[CUR] - current.yi[CUR];
bdz = current.zf[CUR] - current.zi[CUR];
blength = sqrt((bdx * bdx) + (bdy * bdy) + (bdz * bdz));
N = 1 + blength/delta;
dx = bdx/N;
dy = bdy/N;
dz = bdz/N;
xi = current.xi[CUR];
yi = current.yi[CUR];
zi = current.zi[CUR];
hx = 0;
hy = 0;
hz = 0;
for (I = 0; I<N; I++)


                /*  Biot-Savart Calculation  */
{
xm = xi + (0.5 * (dx));
ym = yi + (0.5 * (dy));
zm = zi + (0.5 * (dz));
bmx = x-xm;
bmy = y-ym;
bmz = z-zm;
rsqd = ((bmx * bmx) + (bmy * bmy) + (bmz * bmz));
rsqdp = rsqd * sqrt(rsqd);
hx = hx + ((dy)*(bmz)-(dz)*(bmy))/rsqdp;
hy = hy + ((dz)*(bmx)-(dx)*(bmz))/rsqdp;
hz = hz + ((dx)*(bmy)-(dy)*(bmx))/rsqdp;
xi = xi + dx;
```

```
        yi = yi + dy;
        zi = zi + dz;
        }
        hx = hx * current.i[CUR]/(4 * pie);
5       hy = hy * current.i[CUR]/(4 * pie);
        hz = hz * current.i[CUR]/(4 * pie);


        field.hx[PTS] = field.hx[PTS] + hx;
        field.hy[PTS] = field.hy[PTS] + hy;
10      field.hz[PTS] = field.hz[PTS] + hz;
        }
        }


        /* Tabulate and plot results */
15      fprintf(fp,"\n");
        fprintf(fp,"Current elements\n");
        fprintf(fp," i    xi   yi   zi   xf   yf   zf\n");
        for (CUR=0; CUR<NCUR; CUR++)
            {
20          fprintf(fp,"%+.2f %+.2f %+.2f %+.2f %+.2f %+.2f %+.2f\n", current.i[CUR],
        current.xi[CUR], current.yi[CUR], current.zi[CUR], current.xf[CUR], current.yf[CUR],
        current.zf[CUR]);
            printf("current element\n");
                    plot_current(current.xi[CUR]-0.5, current.yi[CUR]+2.0,
25      current.xf[CUR]-0.5, current.yf[CUR]+2.0, 425);
                    plot_oblique(current.xi[CUR]-0.5, current.yi[CUR],
        current.zi[CUR]+0.00, current.xf[CUR]-0.5, current.yf[CUR], current.zf[CUR]+0.00,
        425);
                    };
30      for (CUR=0; CUR<NCPERS; CUR++)
            {
                    plot_current(current.xi[CUR]-1.00, current.yi[CUR]-0.22,
        current.xf[CUR]-1.00, current.yf[CUR]-0.22, 4250);
```

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```
                    }

    fprintf(fp,"\n");
    fprintf(fp,"Magnetic field\n");
5   fprintf(fp,"   Hx      Hy      Hz     x    y    z\n");
    for (PTS=0; PTS<NPTS; PTS++)
        {
    fprintf(fp,"%+.2e %+.2e %+.2e %+.3f %+.3f %+.3f\n", field.hx[PTS], field.hy[PTS],
    field.hz[PTS], field.x[PTS], field.y[PTS], field.z[PTS]);
10      printf("mag field\n");
                    plot_field(field.x[PTS]-1.00, field.y[PTS]-0.22, field.hx[PTS],
    field.hy[PTS], 4250, 14);
                    };
                        output_graph();
15      exit (0);
    }
```